Development of physical and mathematical models describing ionization mechanisms for neutral gas jets produced by conventional thrusters and other onboard systems

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Abstract

The present report is the third and final deliverable according to EOARD Contract SPC-94-4080, item 0003.

The paper contains the description of the code to calculate the parameters of gas-plasma formations (GPF) arising as a result of ionization of neutral gases released from a spacecraft due to action of space flight factors including ultraviolet radiation and ram ionospheric flow, representative samples of calculations and Comparison of results obtained with available data on interaction of gas releases with environment User's Manual of Program GPF developed, is presented in Appendix.

Nomenclature

$a(x)$ - cross sectional size of gas jet

b - spatial scale of arising GPF

c - thermal velocity

$k=1/(a'_m)^2$ - factor of flow divergency

$\dot{N}$ - particles flow rate

n - particles concentration

n_m - density scale value

n_1, v_1 - concentration and velocity of ram flow particles

n_2, v_2 - concentration and velocity of newly generated particles

q_1 - effective cross sectional area of ram flow particles absorption by the jet substance

q_2 - effective cross sectional area of second kind particles generation

q_3 - effective cross sectional area of disappearence

t - lifetime of second kind particles

T - electron temperature

x, r, φ - cylindrical coordinates

u, v - x- and r- components of flow velocity

x, y, z - Cartesian coordinates

β - angle between gas jet axis and ionizing flux direction

γ - specific heat ratio

λ - ion mean free path

$\eta = \frac{r}{x}\sqrt{k}$ - self-similar variable

ρ, θ, φ - polar coordinates

$\tau_i(\eta) = \frac{T}{T_c}$ - demensionless temperature

Subscripts:

$_0$ - initial quantity

$_1$ - ram flow particles

$_2$ - newly generated particles

$_c$ - quantity at flow axis

$_m$ - maximal quantity

prime denotes spatial along axis x derivative.

Content

Introduction

The objectives of the work is development of physical and mathematical models describing ionization mechanisms for neutral gas jets released from a spacecraft with due regard to the main factors of space flight including ultraviolet radiation and ram ionospheric flow.

These models are intended to predict the behavior of artificial gas-plasma formations (GPF) arising in space particularly in vicinity of a spacecraft as the typical result of normal operation of certain onboard systems including conventional gas thrusters, life-support, heat- control and other systems which operation is accompanied by release of neutral gases with their exposition to action of space flight factors.

Knowledge of the GPF characteristics is important for determination of communication, navigation and ranging conditions, for evaluation of GPF influence on spacecraft environment and consequently on sensitive onboard equipment operation.

The previous intermediate report submitted as the second deliverable according to EOARD Contract SPC-94-4080, item 0002, contains the analyzes of ionization mechanisms dominating in interaction of gas releases from a spacecraft with the space fluxes of high energy, dynamical problem formulation and general and particular solutions describing evolution of arising artificial gas-plasma formations.

It is assumed that injected gas flow is exposed to uniform rarefied high energy fluxes (particles and quantums) in outer space. Absorption of this fluxes slightly modifies the initial distributions of injected gas parameters which are described by the system of equations for partially ionized plasma. The parameters

distributions of the resultant GPF are the main issues of the study.

Under reasonable assumption the system of equations for three-dimensional gas flow was sufficiently reduced. For certain axial symmetrical cases the self similar approach reduces the problem to quadratures and to solution of combined ordinary differential equations. However general solution of this system is not analytical and requires numerical calculation.

The next section reproduces the basic physical approaches and theoretical issues of report [5], used for development of PC Program for calculation of parameters of gas-plasma formations arising as a result of ionization of neutral gases released from a spacecraft due to action of space flight factors.

The following section contains a general description of the Program and the representative samples of calculations.

The third section presents the comparison of theoretical results obtained with appropriate published data.

1. Basic physical approaches describing interaction of gas releases from a spacecraft with environment

Current researches on mechanisms of interaction between exhausted plumes and space background media are predominantly concentrated to the processes that take place on atomic and/or molecular levels. Many specific integral characteristics of the resulting GPF may be understood taking into account only dominant simple kinds of interaction between released gases and the space fluxes.

It is assumed that injected gas flow is exposed to uniform rarefied high energy fluxes (particles and quantums) in outer space.

Absorption of this fluxes slightly modifies the initial distributions of injected gas parameters which are described by the system of equations for partially ionized plasma.

Solutions of this two- or three- dimensional problem may be obtained in relatively simple and representative forms using the following assumptions.

For many real situations the injected gas jet is much more dense than incident flows of particles or quantums. Densities of energy, impulse and substance fluxes in these flows are negligible compared to those of the injected gas jet. Therefore the interaction of the incident highly energetic flows with the gas jet changes the content of the latter (for instance shares of its ionized and/or exited species) with practically no change in its dynamical characteristics. Consequently the intensity of the incident fluxes decreases. Quantums vanish due to photo ionization, ions of high energy disappear due to charge exchange etc. It is also assumed that all processes are determined by pair collisions.

Ionization Mechanisms of Gas Releases in Space

The main ionization mechanisms of gas releases in space are the following:

1) gas photo ionization with ultraviolet part of the Sun radiation spectrum;

2) raking of the ambient plasma up due to elastic collisions and charge exchange of ionospheric ions O^+, O^+_2, N^+ with released atoms;

3) ionization due to chemical reaction of the ambient oxygen atoms with released molecules and radicals;

4) released gas ionization by ionospheric electrons;

5) released gas ionization by atmospheric molecules N_2, O_2 and oxygen atoms O incident upon with energy of relative orbital motion of about 8 km/s;

6) ionization by space electron fluxes with energy of over 40 eV.

Table 1 displays the relative intensities of ionizing mechanisms mentioned above for orbital velocity of about 8 km/s.

Table 1

Ionization mechanisms	Particles flow density $cm^{-2}s^{-1}$	Energy flux density $eVcm^{-2}s^{-1}$
Photo ionization		
$h\nu > 3.9$ eV	$5x10^{15}$	$2x10^{16}$
$h\nu > 7.9$ eV	10^{12}	10^{13}
Ionospheric raking effect at altitude H = 360 km	10^{12}	-
ionization by:		
-ionospheric random electrons	10^{12}	10^{11}
-energetic particles flux	10^{8}	10^{12}
-shock ionization at altitude		
H = 360 km	10^{14}	10^{15}
H = 200 km	10^{16}	10^{17}

Table 1 suggests that the most effective ionizing mechanisms are photo ionization and shock ionization by particles of ram "wind". The relative role of this mechanisms depends on the released substance and the orbit altitude.

Problem Formulation

A source being placed at the origin of cylindrical coordinates, x=0 and r=0, releases a gas jet along x axis. Gas flow velocity is constant along every flow line so that $u = u_m Y(\eta)$ and

$a'=a'_m$ =const. The gas density and velocity components distribution may be given by (See Ref. 5,8):

$$n = \frac{N\,(\gamma - 1/2)k}{\pi\, x^2\, u_m} f_n\,(\eta);\quad f_n\,(\eta) = \frac{1}{\tau\,(1+\eta^2)};\quad \eta^2 = \frac{kr^2}{x^2};$$
$$u = u_m Y(\eta);\quad v = ua'\eta;\quad Y(\eta) = \left(\frac{\tau}{1+\eta^2}\right)^{1/2};\quad k = \frac{1}{(a'_m)^2}. \qquad (1)$$

This gas jet is exposed to an uniform ram flow of particles of concentration n_1 and velocity u_1.

Collisions between particles of the gas jet and the ram flow generate new particles, i.g. ions of concentration n_2 and velocity u_2. For practice the following conditions are real:

1) the gas jet velocity u is much less compared to the ram flow velocity u_1.

2) the ram flow, $n_1 u_1$, vanishes in the gas jet but does not noticeable disturbs its temperature, velocity and content so that

$$n_2 = \frac{n_1 u_1}{u_2} \ll n$$

3) a free path of newly generated particles is negligible compared to characteristic size "b" of disappearance of the ram flow particles.

Size "b" is evaluated below.

Under these condition the parameters of exposed gas jet do not depend on mechanisms of its interaction with the ram flow and newly generated particles follow the practically unperturbed gas jet, so that $u_2 = u$, $v_2 = v$ and $T_2 = T$. Particularly the conditions mentioned above are satisfied if the ram flow represents photons else where, or ions (the raking effect) in ionosphere, or neutral particles (shock ionization) in the upper atmosphere.

For solution of the problem postulated above there is no need in equations of motion and energy for disappearing and newly

generated particles. Therefore the problem is reduced to two equations of continuity:

$$\Delta\, n_1 \vec{u}_1 = q_1\, nn_1 |\vec{u}_1| ;$$
$$\Delta\, n_2 \vec{V} = q_2\, nn_1 |\vec{u}_1| ; \qquad (2)$$

where q_1 is the effective cross sectional area of the prime kind particles absorption by the jet substance and q_2 is that one of the second kind particles generation (i.e., ionization).

The values of concentration, n, and vector $\vec{V}$ components are defined by equations (1).

For photo ionization and the raking effect $q_1 = q_2$ and $q_1 > q_2$ for gas ionization due to collisions with heavy particles.

Analytic Solution for Axially Symmetrical Plasma Formations

For a gas jet directed upward the ionizing flux the general solution of the linear system (2) is written as

$$n_1 u_1 = (n_1 u_1)_o \exp\left(-\frac{b}{x} f_1\right); \quad f_1(\eta) = \frac{1}{\eta}\int_0^{\eta} f_n(t)\, dt;$$
$$n_2 = n_m f_2(\eta)\, \frac{F(p)}{F_m}; \quad f_2 = \frac{f_n}{f_1 Y}; \quad p = \frac{x}{b f_1}; \qquad (3)$$
$$F(p) = \frac{1}{p}\exp\left(-\frac{1}{p}\right) + \frac{1}{p^2}\,\varepsilon_i\left(-\frac{1}{p}\right);$$
$$F(p) \underset{p \to \infty}{\longrightarrow} \frac{1}{p};$$
$$n_m = \frac{(n_1 u_1)_o F_m}{u_m}\,\frac{q_2}{q_1}; \qquad b = \frac{q_1 \dot{N}(\gamma^{-1}/_2)k}{\pi u_m},$$

where $(n_1 u_1)_o$ is the ionizing flux density at $x \to \infty$;

$\varepsilon_i(-1/p)$ is the exponential integral function;

n_m is a density scale value;

b is a spatial scale of the arising GPF and

$F_m = 0.166$ is the maximal value of function F(p) at p = 1.66.

The value of n_m depends on the density $(n_1 u_1)_0$ of the rarefied ionizing flux, the relative effectiveness of ionization, q_2/q_1, and the expansion velocity of plasma formation, u_m. The plasma formation size depends only on the gas jet parameters and on the effective cross sectional area of absorption, q_1.

For a gas jet directed downward the ionizing flux, i.e. for $u_m<0, x<0$ and $a'<0$, the distributions of plasma parameters may be written as:

$$n_1 u_1 = (n_1 u_1)_0 \exp\left(-\frac{b}{x} f_1\right) ; \quad f_1(\eta) = -\frac{1}{\eta} \int_{\eta}^{\infty} f_n(t)\, dt;$$

$$n_2 = n_m f_2 \frac{F(p)}{F_m} ; \quad f_2 = \frac{f_n}{|f_1| Y} ; \quad p = \frac{x}{b f_1} . \tag{4}$$

For spherically symmetrical gas expansion in polar coordinates ρ and θ the solution appears as:

$$n = \frac{\dot{N}}{4\pi\rho^2 u_m} ; \quad n_1 u_1 = (n_1 u_1)_0 \exp\left(-\frac{b}{\rho} \frac{\theta}{\sin\theta}\right) ;$$

$$n_2 = n_m \frac{\sin\theta}{\theta} \frac{F(p)}{F_m} ; \quad p = \frac{\rho}{b} \frac{\sin\theta}{\theta} ; \quad b = \frac{q_1 \dot{N}}{4\pi u_m} . \tag{5}$$

General Solution for Three-Dimensional Plasma Formations

With arbitrary chosen angle β between the velocity vectors of the released gas jet and the ionizing flux the resulted plasma formation is three-dimensional with the symmetry plane defined by

the velocity vectors mentioned above. Again the equations of continuity (2) are used to formulate the problem. As soon as processes of interaction of the released gas jet and the ionizing flux are described by relationships (1) the solution in polar coordinates ρ, Θ, φ, is analogous to formulas (3) with the following definitions of functions f_1 and p:

$$p = \frac{\rho \cos \Theta}{b\ f1} \ ;$$

1) for $0 < \beta < \pi/2$:

$$f_1 = c \int_{t_1}^{t_2} \frac{dt}{(1+t^2)} \ ;$$

2) for $\pi/2 < \beta < \pi$:

$$f_1 = - c \int_{t_1}^{\infty} \frac{dt}{(1+t^2)} \ ;$$

$$c = \frac{1}{\sqrt{k}\ \cos\beta\,(tg^2\Theta+tg^2\beta-2tg\Theta tg\beta\cos\varphi)^{1/2}\left(1+\frac{k\ tg^2\Theta\ tg^2\beta\ \sin^2\varphi}{tg^2\Theta+tg^2\beta-2tg\Theta tg\beta\cos\varphi}\right)^{\gamma-1/2}}$$

$$t_1 = \frac{\sqrt{k}\ \ tg\ \Theta\ (tg\ \beta\ \cos\ \varphi - tg\ \Theta\ )}{(tg^2\Theta+tg^2\beta-2tg\ \Theta\ tg\ \beta\ \cos\ \varphi + k\ tg^2\Theta\ tg^2\beta\ \sin^2\varphi)^{1/2}} \ ;$$

$$t_2 = \frac{\sqrt{k}\ \ tg\ \beta\ (tg\ \beta - tg\ \Theta\ \cos\ \varphi)}{(tg^2\Theta + tg^2\beta-2tg\ \Theta\ tg\ \beta\ \cos\ \varphi + k\ tg^2\Theta\ tg^2\beta\ \sin^2\varphi)^{1/2}} \ ;$$

3) for $\beta = \pi/2$:

$$f_1 = \frac{1}{\sqrt{k}\ (1+\ k\ tg^2\Theta\ tg^2\beta\ \sin^2\varphi)^{\gamma-1/2}} \int_{t_0}^{\infty} \frac{dt}{(1+t^2)} \ ;$$

$$t_0 = \frac{k^{1/2}\ \ tg\ \Theta\ \cos\ \varphi}{(1\ +\ k\ tg^2\Theta\ \sin^2\varphi)^{1/2}} \ .$$

Presented above formulas are basic for three-dimensional calculations realized in PC **Program** GPF.

2. PC **Program** GPF for **Calculation** of gas-plasma formations parameters

2.1. General Description of Program

The developed PC **Program** GPF allows to calculate values of electron concentration in an GPF arising as a result of interaction between a rarefied ram flow and an axial symmetrical gas jet or a spherically expanding gas cloud.

This GPF is three dimensional with a plane of symmetry defined by velocity vectors of the jet and the ram flow.

Equations (3 - 6) defining concentration of newly created charged particles, n_2, and of background media ones, n_1, respectively are subjects of subsequent numerical calculations. In dependence on the type of dominant reaction the total electron concentration is equal :

$n = n_2$ for photo and/or shock ionization;

$n = n_1$ for electrophile substances, producing an "ionospheric hole";

$n = n_1 + n_2$ for charge exchange reaction.

The function EXPINT is used for calculation of the exponential integral function and procedure QUANC8 or SIMPSON are used for calculation of definite integrals in formulas (3 - 6).

For three-dimensional GPF the code calculates :

1) value of plasma concentration in arbitrary chosen point (x,y,z) of Cartesian coordinates with axis x directed along the gas jet axis and xz plane being the plane of GPF symmetry;

2) plasma concentration distribution along given gas flow line;

3) plasma concentration distribution along given Cartesian coordinate with two other coordinates fixed;

4) lines of equal concentration in the plane of GPF symmetry.

5) lines of equal concentration in transverse planes.

The input data are characteristics of the released gas jet, the ionizing flux, constants of reactions and a problem geometry.

2.2. Representative samples of calculations.

Fig. 1 shows the distribution of electron concentration for the gas jet directed upward the ionizing flux with dimensionless coordinates:

$$\hat{r} = \frac{r\sqrt{k}}{b}, \quad \hat{x} = \frac{x}{b}.$$

Fig. 1 displays the plasma formation shape for $\tau = 1$ corresponding to the thermal mode of the released gas flow with uniform transverse temperature. Fig. 2 displays the plasma formation shape for a gas jet directed downward the ionizing flux, i.e. for $u_m < 0, x < 0$ and $a' < 0$. For spherically gas symmetrical expansion in polar coordinates ρ and θ the resultant plasma formation shape appears as shown in Fig 3.

Particularly a representative sample of such calculations shows that release of non-readily-ionizing gas (i.g. N_2) with mass flow rate of 100 g/s and velocity of 255 m/s so that the angle between the jet axis and the spacecraft velocity vector is 135° results in appearance of three-dimensional GPF with characteristic size of 190 m and maximal plasma concentration of $5*10^6$ cm^{-3} due to raking up of the ionospheric plasma if concentration of the latter is equal to 10^6 cm^{-3}.

Fig. 4 and 5 demonstrate a peculiar GPF with two maximums in spatial distribution of plasma concentration.

As an another representative sample Table 2 summarizes plasma parameters in Cesium vapor jet with mass flow rate of $m = 2.2$ g/s and $N = 10^{22}$ s^{-1} expanding with $a' = 0.3$ and velocity $u_m = 2 \cdot 10^2$ m/s.

Here the effective cross sectional area of Cesium vapor ionization, q_2, is taken equal to $5*10^{-19}$ cm^{-2} for photo process from Ref. 3 and to 10^{-17} cm^{-2} from Ref. 4 for shock ionization by atoms N_2 incident upon with relative velocity of 8 km/s whereas the effective cross sectional area of elastic collision for this pair, q_1, is equal to $2*10^{-16}$ cm^{-2}.

Table 2

Ionization mechanism	(n_1, u_1), $cm^{-2} s^{-1}$	n_m, cm^{-3}	b, m	x_n, m	$2r_n$, m
Photo ionization	$5x10^{15}$	$4x10^{10}$	10^{-2}	$4x10^2$	10^2
Shock ionization at altitude					
H = 360 km	10^{14}	$4x10^7$	3	60	15
H = 200 km	10^{15}	$4x10^8$	3	$6x10^2$	$1.5x10^2$
Ionospheric"snow-plow" at H = 360 km	10^{12}	10^7	3	3	0

The last two columns of Table 2 present evaluated for $\tau = 1$ longitudinal and transverse dimensions, x_n and $2r_n$, of the plasma formation at the concentration level of $n_2 = 10^7$ cm^{-3}.

Therefore due to the Sun radiation energy and/or kinetic energy of an orbiting spacecraft not very dense but large scale plasma inhomogeneities may arise in vicinity of a gas releasing spacecraft in LEO with subsequent impact to RF wave propagation of the metric range.

3. Comparison of results obtained with available data on interaction of gas releases with environment

In Ref. [7] a specific glow was observed in the exhaust plume of the Space shuttle PRCS engine firing directly into oncoming atmosphere. It was shown that the observed glow is quenching of exited O (^{1}S) state due to collisions of atmospheric oxygen atoms with exhausted H_2O molecules. In this experiment the collision velocity is ~ 11.3 km/s resulting in a center-of-mass collision energy in excess of 5 eV so that there is sufficient excitation energy for O (^{1}S) state in the ram plume. The presented in Fig.2 of Ref. [7] spatial distribution of O (^{1}S) emission intensity in the field of view of the spectrograph used, is below compared with calculations according to our method. The numerical evaluation of O (^{1}S) emission line intensity is also presented in comparison with data of Fig.4 in Ref.[7].

According to the mathematical model presented in Report [5], interaction between released gas and oncoming background flow results in generation of particles of "new kind" which further do not vanish.

The oncoming flow being rarefied enough, does not impact dynamics of the released gas jet. The analysis presented in Ref. [5] suggests that excitation and de-excitation of O (^{1}S) state may occur in a few concurrent reactions. Data on reaction rate accumulated in Tab.2 of Ref. [7] allow to choose the dominant reaction resulting in the following continuity equation for O (^{1}S) specie:

$$\frac{\partial n_2 u}{\partial x} + \frac{\partial (r\, n_2\, v)}{r\, \partial r} = \langle q_2 c_2 \rangle\, nn_1 - \frac{n_2}{t} - \langle q_3 c_2 \rangle\, nn_2 \qquad (6)$$

Here n_2 - concentration of O (^{1}S) atoms;

u and v - velocity components released jet;

n - concentration of H_2O molecules in the jet;

t - life time of exited O (^1S) state;

q_2, q_3 - excitation and de-excitation cross sectional areas for O (^1S) state.

According to Tab.2 of Ref.[7] exited atoms O (^1S) are produced mainly in reaction :

$$O\ (^3P) + H_2O \rightarrow O\ (^1S) + H_2O;$$

For this reaction $\langle q_2 c_2 \rangle = 1.5\ 10^{-13} \exp(-E_A/E) = 7.1\ 10^{-14}$ cm^3/s, E_A = 4.2 eV and E = 5.7 eV corresponding to a center-of-mass collision energy of species O and H_2O for relative velocity of 11.2 km/s.

Quenching of exited O (^1S) state may occur either due to the radiative decay processes with characteristic lifetime of t=4 s or as a result of collisional reactions

$$O\ (^1S) + H_2O \rightarrow O\ (^1D) + H_2O \quad \text{with } \langle q_3 c_2 \rangle = 1.5\ 10^{-10} \text{cm}^3/\text{s}$$

$$O\ (^1S) + H_2O \rightarrow OH + OH \quad \text{with } \langle q_3 c_2 \rangle = 3\ 10^{-10} \text{ cm}^3/\text{s}$$

so that $\langle q_3 c_2 \rangle = 4.5\ 10^{-10}$ cm^3/s.

Using analytical expression for n_2 from Report [5] let us evaluate relative values of right hand members in Eq.(6). If particles O (^1S) do not vanish in the gas jet, their concentration would reach its maximal value

$$n_m = \frac{n_1 \langle q_2 c_2 \rangle}{6\ u_c\ q_1}$$

at a distance from nozzle exit orifice :

$$\Delta X = \frac{\dot{N}\ \nu\ k\ q_1}{\pi\ u_c}\ 1.66$$

Here $\dot{N}$ = 3.35 10^{25} 1/s is particles flow rate in the exhaust

of PRCS engine;

u_c = 3.5 km/s is the exhaust velocity;

k = 8.0 is the divergency factor taken the same as for engine, mentioned in Ref. [8], section 3.2;

$\nu = \gamma - 0.5$ is the constant in expression for distribution of jet parameters;

n_1 and u_1 are density and velocity of oncoming flow of oxygen atoms and q_1 is the effective cross sectional area of momentum exchange of for oncoming flow of oxygen atoms.

For altitude 325 km we assume $n_1 = 5 \cdot 10^8$ cm^{-3}. The effective cross sectional area, q_1, of multispecie jet is evaluated as

$$q_1 = \sum_i \alpha_i \, q_i$$

Here α_i is a mole share of the jet i-specie;

In the far region of the jet where x»b, we obtain : $n_2 = 10 \, n_m b/x$ and where $x \ll b$ $n_2 = n_m \exp(-b/x)$.

Therefore the above evaluated maximal emission intensity scale $I \sim n_m b / t = 0{,}35 \; 10^9$ $1/(cm^2 \; s)$, agree with data computed by program SOCRATES and shown in Fig.6 of Ref. [7].

Evaluation of the right hand members in the continuity equation suggests that processes diminishing exited oxygen atoms, may be ignored. De-excitation rate of O (^{1}S) state (the last member) is low compared to excitation rate (the first member) since the necessary condition of

$$n_2 < n_1 \frac{\langle q_2 c_2 \rangle}{\langle q_3 c_2 \rangle}$$

is satisfied even at maximum of $n_2 = n_m$ and surely everywhere.

The radiative decay rate of O (^{1}S) state is even lower since

$$n_2/t < n \, n_2 \langle q_3 c_2 \rangle \quad \text{for} \quad x < \left(\frac{N \nu k \langle q_3 c_2 \rangle \tau}{\pi u_c} \right)^{1/2} = 7.1 \text{ km}$$

Therefore the distribution of exited O (^{1}S) atoms in the experiment of Ref. [7] may be described correctly enough with the mathematical model presented in Ref. [5].

Particularly numerical evaluation of 577.7 A line emission intensity in the geometry of Fig. 3. in Ref. [7] gives the value of ~ 3 kR for the region adjacent to the boundary of the spectrometer field of view (see Fig. 6) , whereas the actually measured one is 3.5 kR [7]. This agreement is good enough for the greatly simplified method of calculation used. Note that the line-ofsight intensity for the O (^{1}S) emission was of the order 2 kR as calculated by compex SOCRATES code [9].

Discussion

The flow field model presented, describes the self-consistent mechanisms transforming the content of released dense gas flow due to interaction with the rarefied uniform oncoming flux of high energy and disappèarence of the latter as it propagates through the dense gas flow.

To obtain analytical solutions of two-dimensional problems resulting in relatively compact algorithms of numerical calculation, the following conditions are used:

- generation of "new" particles is characterized with the only effective cross sectional area for dominant process so that concurrent non-dominant processes are ignored;

- absorption of high energy flux is also characterized with the only effective cross sectional area summing all sufficient mechanisms of absorption and/or scattering of flux energy;

- the oncoming high energy flux does not disturb the dynamical characteristics of released gas flow since concentration of particles "newly" generated due to the intercalation, is relatively low;

- all processes are of only one step with no further transformation of the "newly" generated particles.

These condition are readily met in many situation being interacting for practice including:

- photo ionization of freely expanding gas flow when recombination is insufficient;

- raking of oncoming ambient plasma up by a gas target if recombination processes are "frozen" due to effective expansion;

- any special situations like that described in the previous section.

However there is a lot of real situations where the conditions

mentioned above, are not satisfied.

Preliminary analysis suggests that the self-similar approach may be further improved with the following corrections and modifications:

- taking into account disturbance of the dense gas flow due to spatially distributed absorption of the high energy flux;

- involving the recombination or de-excitation processes due to either the radiative decay or to pair collisions with known life times;

- taking into account concurrent processes of "new" particles generation due to independent mechanisms (i.g. Sun light photo ionization and raking of the oncoming flux up);

- analyzing new variants of parameters distributions in gas flows (see [8]).

Conclusion

Neutral gases released from a spacecraft because of normal operation of certain onboard systems including conventional gas thrusters become partially ionized being exposed to action of space flight factors.

The resulting gas-plasma formations (GPF) behavior is described by the system of equations for weakly ionized plasma. The parameters distributions of the resultant GPF are the main issues of the study.

For many real situations the injected gas jet is much more dense than incident flows of particles or quantums. Densities of energy, impulse and substance fluxes in these flows are negligible compared to those of the injected gas jet. Therefore the interaction of the incident highly energetic fluxes with the gas jet changes the content of the latter (for instance shares of its ionized and/or exited species) with practically no change in its dynamical characteristics.

Under these assumption the system of equations for three-dimensional gas flow was reduced to the continuity equations for arising and disappearing particles. General solution of this equations is not analytical and requires numerical calculation.

For certain axially symmetrical cases the self similar approach allowed to reduce the problem to quadratures and to solution of combined ordinary differential equations.

The developed mathematical model describing interaction of neutral gas jets released from a spacecraft with high energy fluxes in space, allows for quantitative evaluation of relevant ionization mechanisms including:

- photo ionization of gas released by the Sun radiation;

- raking up of ionospheric particles by the gas released;

- shock excitation and/or ionization of gas released by particles of incoming ram "wind".

The relative role of this mechanisms depends on the released substance and the flight conditions.

Validity of theoretical result obtained is evaluated by the way of comparison with published data on interaction of gas releases with flight environment. Particularly the emission spatial distribution and intensity in the Space Shuttle glow experiment is correctly described with the mathematical model presented.

The obtained dynamical problems solutions were put in the base of PC Program GPF developed to calculate characteristics of gas-plasma formations expected to arise in vicinity of a gas releasing spacecraft.

The Program GPF allows "to visualize" plasma flow field and provides data for numerous application including i.g. RF refraction / scattering calculations, necessary for determination of communication, navigation and ranging conditions for a spacecraft.

The representative samples of calculation suggest that due to the Sun radiation energy and/or kinetic energy of an orbiting spacecraft not very dense but large plasma formations may arise in LEO as a result of gas releases.

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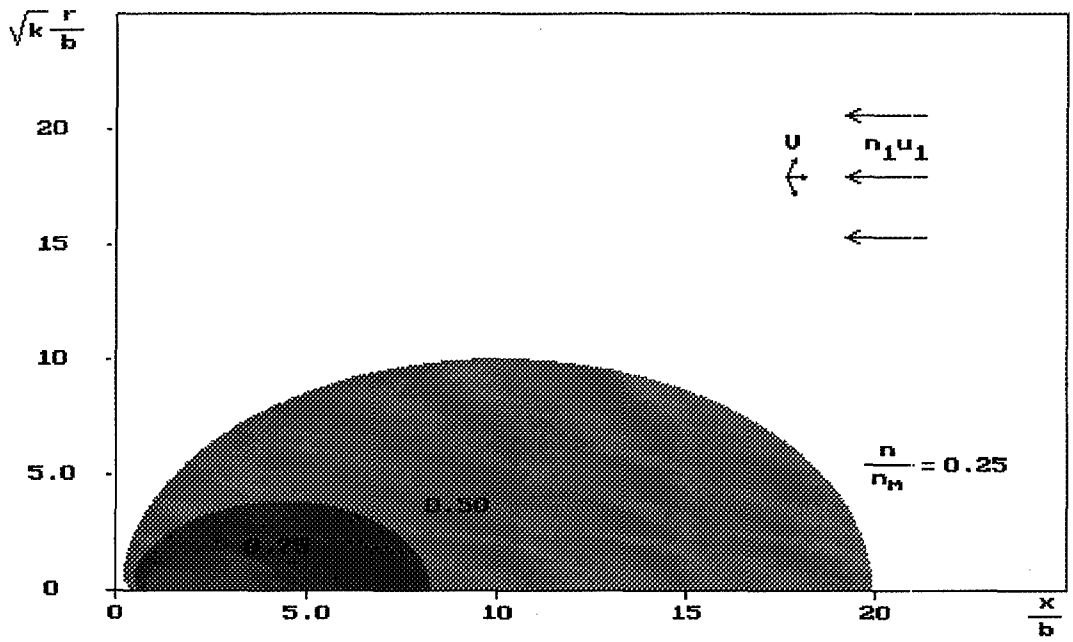


Fig.1 The lines of equal plasma concentration in the symmetry plane of the resulting plasma formations when the gas jet is directed upward the ionizing flux

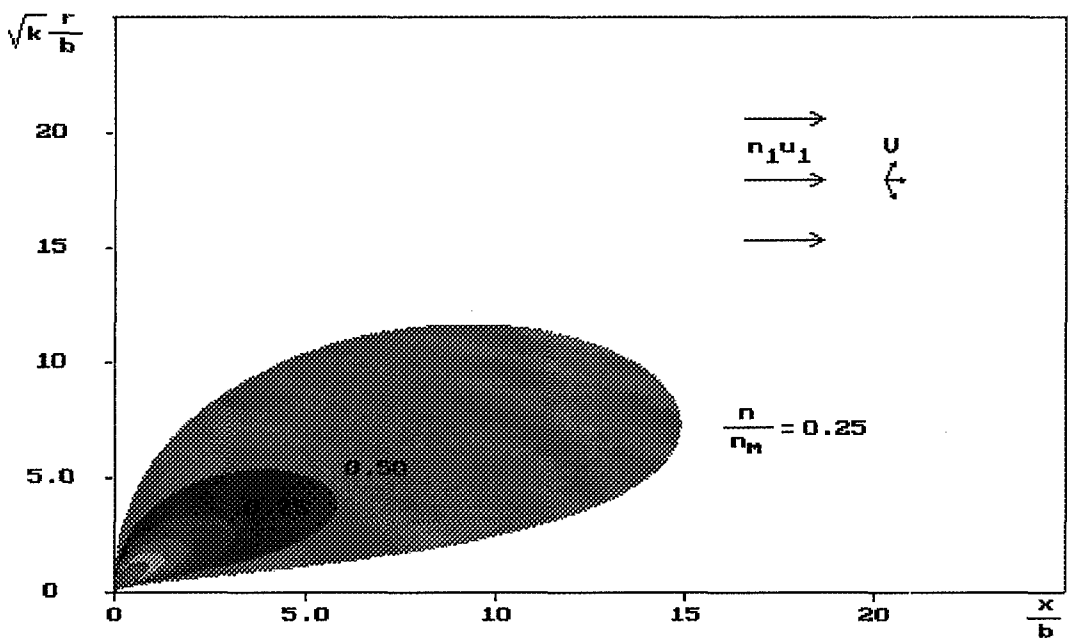


Fig.2 The lines of equal plasma concentration in the symmetry plane of the resulting plasma formations when the gas jet is directed downward the ionizing flux.

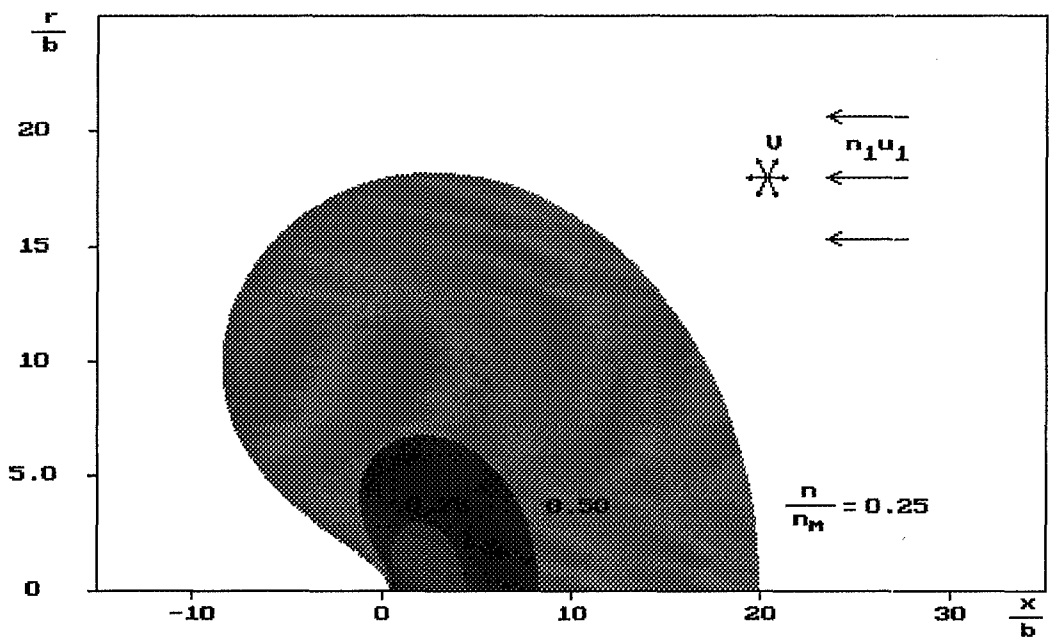


Fig.3 The lines of equal plasma concentration in the simmetry plane of the resulting plasma formations for spherically symmetrical gas expantion.

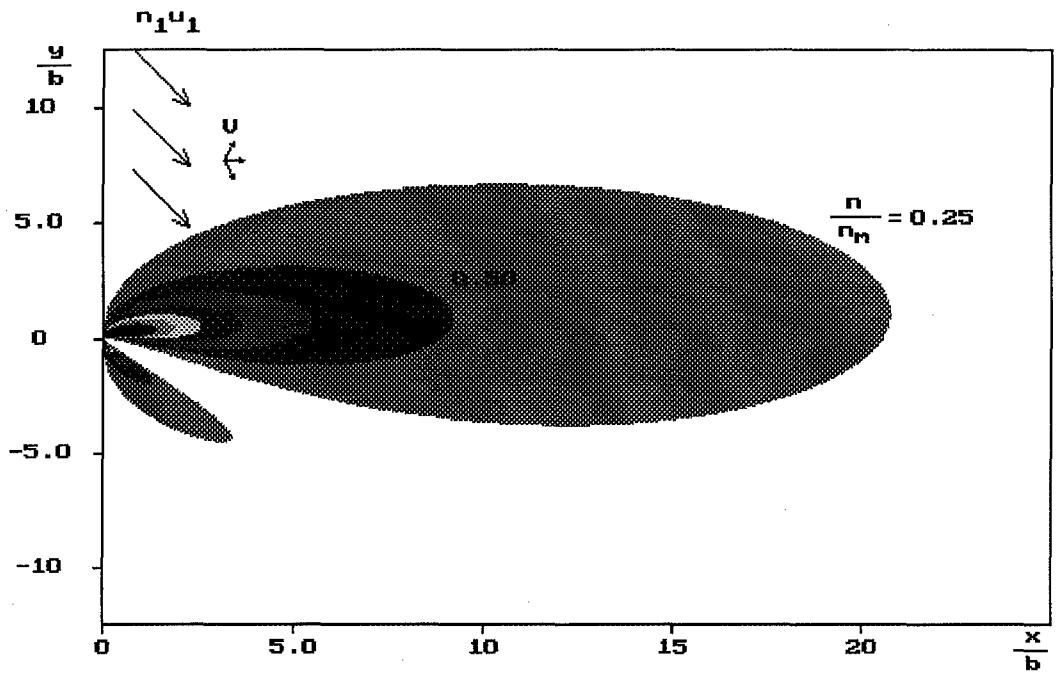


Fig.4 The lines of equal plasma concentration in the symmetry plane of plasma formations for $\beta = 135$, $k = 3.31$, $\gamma = 1.4$

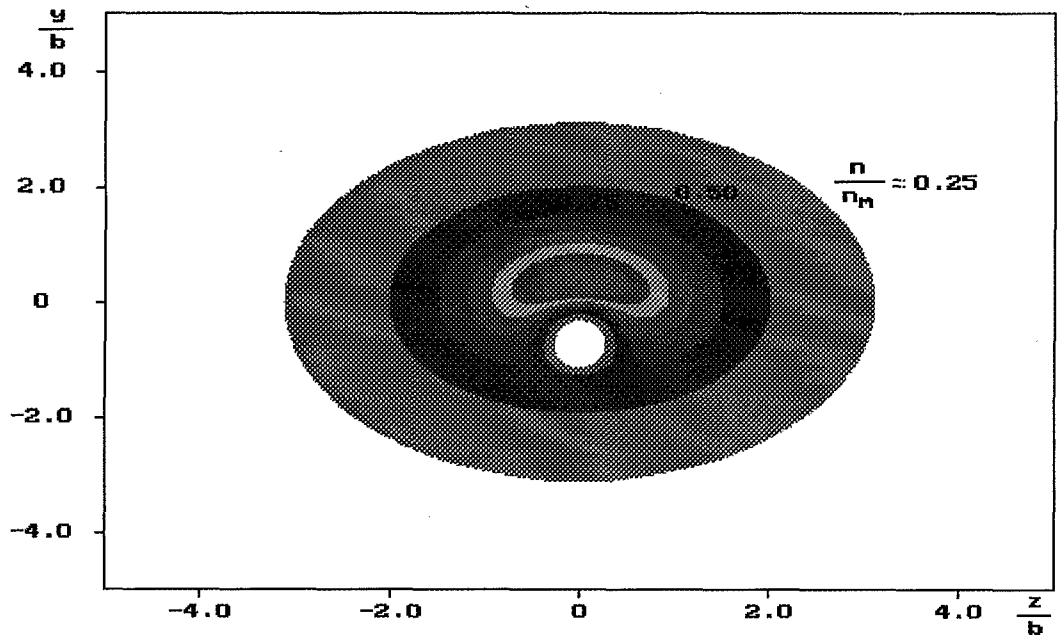


Fig.5 The lines of equal plasma concentration in the cross sectional planes, normal to the gas jet axis for x/b = 1.0.

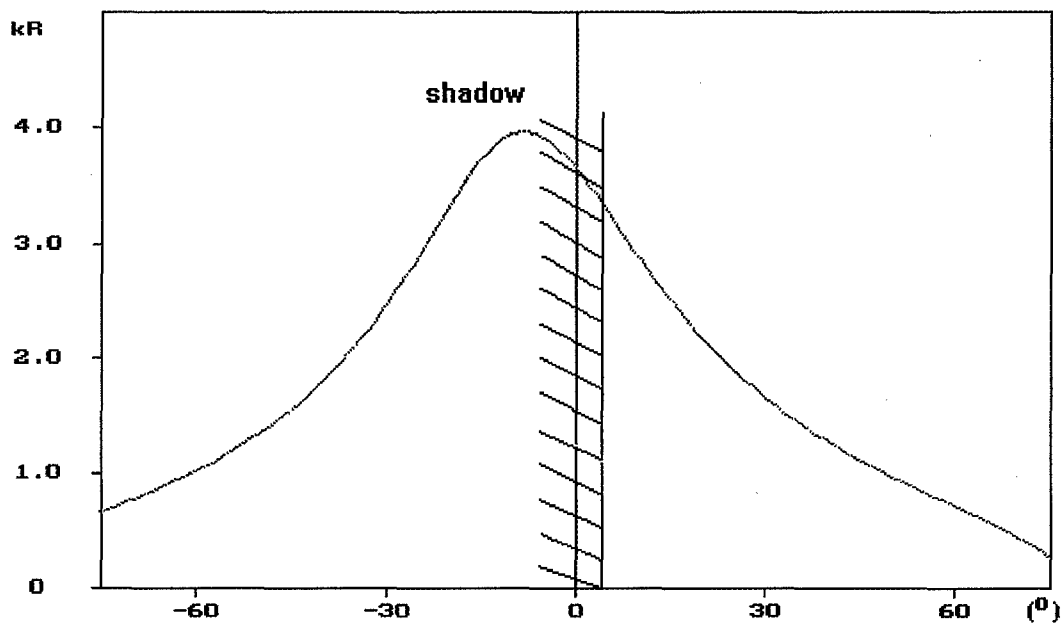


Fig.6 Vertical intensity distribution for the 557.7 nm emission in the geometry of Fig.3 in Ref[7].

Program GPF

User's Manual

To put GPF.EXE run You need a computer with 80286 processor (or higher) and more than 1 megabytes memory available.

Program GPF.EXE is developed in Borland Pascal 7.01 integrated environment to be run with Microsoft MS DOS 3.3 or later version or compatible one. GPF.EXE uses Turbo Vision and contains a few its Standard Objects (menu bar, screen panel, state line, dialog boxes, mouse support etc.). The following Turbo Vision's standard and demonstration units are implemented: *Gadgets, Objects, Drivers, Memory, Views, Validate, Menus, Dialogs, MsgBox, Calc, App, HelpFile, ColorSel, MouseDlg, Editors, StdDlg.* Borland Pascal's Standard Units *Dos, Crt, Graph, Printer* are also used.

Newly developed units GPFHelp, OPDEC, GPFMain, PCXGR provide the following:

- choice of calculation version;
- data entry, input data correction;
- calculation runs and resultant data soft copy;
- PCX format filing of graphic information and readout to display or 9-pin printer.

Getting GPF.EXE run is simple. Enter the directory containing program GPF.EXE, data file GPF.DAT and help file GPF.HLP, type GPF at DOS prompt and press Enter.

There are two ways to quit the program GPF.EXE. Choose ≡|Exit (or press Alt-X) to quit forever. With the ≡|DOS Shell command, you can leave the program temporarily to perform a DOS command or run another program. To return to GPF.EXE program, type EXIT at the DOS prompt and press Enter. GPF program appears at the state You have leaved it.

GPF program provides easy access to detail information on menu prompts and dialog boxes. Press F1 to open context-sensitive Help window where You can see a text differently colored than environment. This is references. You can use the references to call new window with new information according to the reference You want. Double click mouse on the reference chosen or highlight it with key TAB and press Enter. On the screen "Reference" appeared You also see references and can use them to obtain further information. Press ESC or click CLOSE to put this Help screen away.

Program components

Program GPF contains three visual components: menu bar at the screen top, operating area and status line at the screen bottom. The menu bar is the main access to its items which are most often commands. Choice of command followed by ellipsis (...) opens a dialog box. A command followed by arrow (>) opens a new menu. A command without these symbols performs any action being chosen.

If menu title is highlighted, this menu is active or current one. You can choose menu command using keyboard or mouse. While using keyboard, press F10 to activate menu bar. Choose menu item you want with arrow keys and press Enter. Note: press Esc to cancel.

For more quick access You also can merely press the highlighted letter of the menu name You want. E.g. if menu is active press O to choose command "Option". Also You can press Alt and while holding this key down, press the highlighted letter without first opening the menu.

While using mouse firstly click menu title and then the command You want. Note: You can adjust the action of "Ctrl+mouse right button" and even reverse mouse right and left buttons choosing

command "Mouse Options".

You also can drag menu down from the title to a menu command. Release the mouse button on the command You want. (Return the menu to its previous position if You cancel to choose the command.)

Sometimes menu command are dimmed and being chosen, bring nothing. It occurs when the choice of this command is of no sense under current circumstance. E.g. if for given calculation version there is no test example, the choice of any command is of no sense in the Test mode and this command being unavailable is dimmed in menu.

Menu bar becomes invisible if the Program operates in the graphic mode. With the keyboard You can quickly access the menu bar and menu commands using a lot of key combinations ("Hot keys"). You can pass to control menu and activate its items with holding down Alt and pressing a highlighted letter. "Hot keys" can be used elsewhere within the Program as You have no need to open the menu first.

Status line also contains "hot keys". Press "hot key" or click it in the status line to choose command You want. The following Table contain the list of "hot keys" :

key (s)	menu item	action
F1	Help	Open Help Window
F3	Open	Open Dialog Box and access, to file *.PCX of graphic information.
F4		Change of Program mode
F10	(none)	Return to menu bar
Alt-Spacebar	≡ menu	Open E (system) menu
Alt-X	≡|Exit	Terminate Program run with exit to DOS
Alt-O	Options menu	Return to Options menu

Status line appears at the screen bottom and:

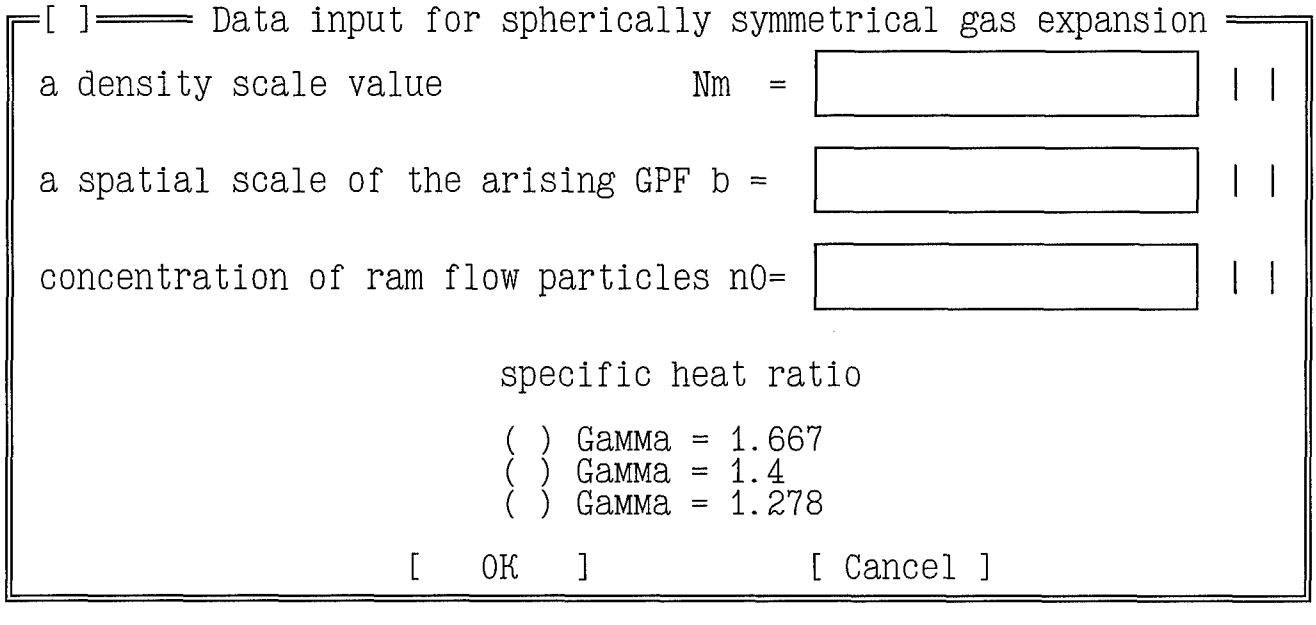
- show "hot key" available in the active window at the moment;

- provides the quickest way to perform any action if You merely click "hot key" in the status line instead choosing menu command or pressing key combination;

- provides short comments on menu command chosen and Dialog box items.

Status line immediately changes if You switch windows or update Program run.

Dialog boxes with ellipsis (...) after a menu command indicates that a dialog box appears when You choose that command. Dialog boxes show and allow to choose a number of options. Within Dialog boxes You can use three screen control elements - option buttons ,action buttons , input boxes. A typical dialog box is below indicated, illustrating these elements:



This dialog box has two standard buttons: OK, Cancel. Pressing OK curries out all choices in the dialog box. If you choose Cancel, nothing changes and no action occurs, and the dialog box is put

away. Command Esc is always equivalent to Cancel button even if the latter is absent in a dialog box.

Using a mouse You need only click the button You want. While using a keyboard You again can merely press highlighted letter to activate the item. E.g. press "O" to choose OK button. Press Tab or shift Tab to move between the items in the dialog box. Every item becomes highlighted as being active.

In a dialog box OK is a default button so that it may be chosen with pressing Enter. If You select any button with Tab, the latter becomes a default button so that it also may be chosen with pressing Enter.

Option buttons always are in a group and only one from the group may be activated at the time. To choose an option button, click it or its text. While using a keyboard, press highlighted letter or repeatedly press Tab until the group becomes highlighted and then use arrow keys to choose one. After choosing new option button, press Tab or Shift-Tab to escape the group.

Probably You are acquainted with input boxes allowing to type a text. For input boxes the main editor keys are available (e.g. Home, End, arrow keys, Insert and other).

If You see a down-arrow icon to the right of an input box, You can get to the history list. The history list attached to an input box lists whatever text you typed the last few times you used the dialog box. You can use the history list to re-enter text that you've already entered. You can also edit an entry in the history list directly. Press Esc to exit from the history list without making a selection.

Program description

Menu bar of Program GPF includes five items:

1. System menu.
2. Spheric.
3. Flow.
4. Options.
5. Read_PCX.

1. System menu.

The System menu appears on the far left of the menu bar and is represented by the ≡ symbol. When you pull down the ≡ menu, you see: About, Calculator, DOS Shell and Exit.

When you choose the About command from the ≡ (System) menu, a dialog box appears, showing copyright and version information. To close the box, press Esc, Space, or Enter, or click the OK button.

When you choose Calculator, a four-function calculator is opened on the desktop. The calculator is a simple four-function calculator with add, subtract, multiply, and divide. To operate the calculator you can either use the keyboard or press the buttons on the calculator with the mouse. The 'C' key clears the calculator, the 'ë' key
toggles the value from positive to negative (the keyboard equivalent of 'ë' is '_').

With the DOS Shell command, you can leave the program temporarily to perform a DOS command or run another program. To return to this program, type EXIT at the DOS prompt.

When you choose the Exit command from the ≡ (System) menu, the Exit command terminates this program.

2. Menu Spheric

Menu Spheric contains commands destined to run calculations and plot graphics for the gas-plasma formation arising when gas expansion is spherically symmetrical.

While activated menu Spheric offers five commands: Calculate_1, Calculate_2, Calculate_3, Calculate_4, Calculate_5.

Action of these commands depends on current operating mode of the Program. A message on current operating mode is highlighted at the far right of the menu bar.

System time and amount of currently available memory are also shown here. Choice of command "Options|Test/Main" or "hot key" F4 switches the Program from mode "TEST" to mode "MAIN" and vice versa. Being switched to mode "TEST" the Program immediately carry out calculations for given test example.

If there is no test example for given command, the latter is unavailable.

Command Calculate_1 calculates a value of plasma concentration at an arbitrary chosen point (x,y,z) of Cartesian coordinates (axis x is directed downward the ionizing flux and xz plane being the plane of GPF symmetry.

Command Calculate_2 calculates a distribution of plasma concentration along given gas flow line.

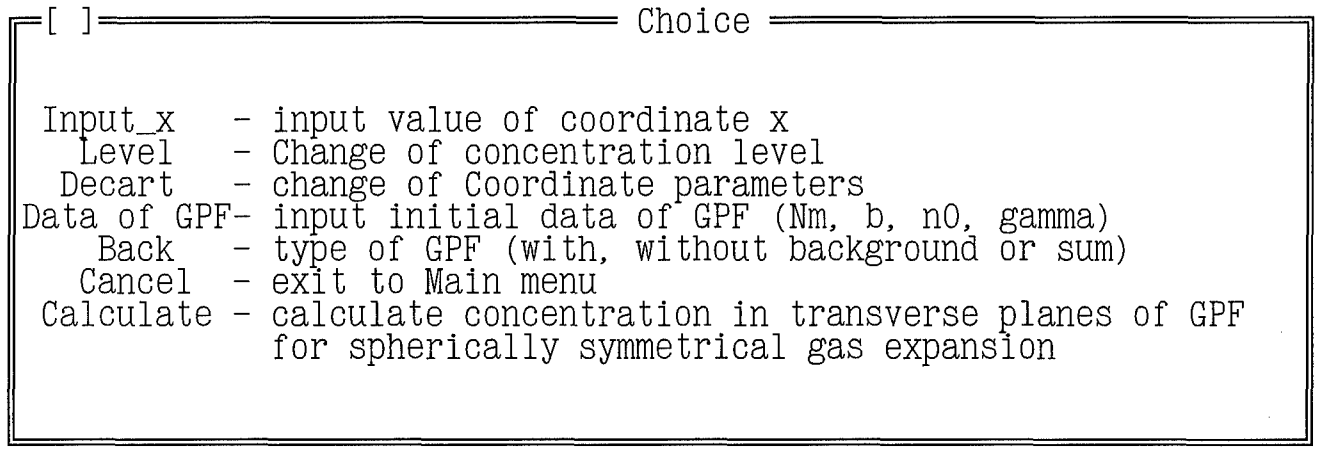
Command Calculate_3 calculates a distribution of plasma concentration along given Cartesian coordinate with two other coordinates fixed;

Command Calculate_4 calculates lines of equal concentration in the plane of GPF symmetry.

Command Calculate_5 calculates lines of equal concentration in

transverse planes i.e. perpendicular to the jet axis for x0 fixed to display GPF spatial configuration.

If the Program is running in the mode "MAIN", the choice of command Sfer-N results in appearance of dialog box "Choice" :



Dialog box "Choice" appears at screen center and You may drag it where You want on the screen. Set the mouse pointer to the top line of the dialog box "Choice", press and hold down the left mouse button while dragging the mouse to new location and release the button.

The dialog box "Choice" has a title bar and close box. If You click this box with the mouse the Dialog box "Choice" disappears. At the left side of the Dialog box "Choice" there is a set of control buttons of rectangular shape. They are often called radio buttons because of their appearance. Every button is provided with a message informing what happens if You press it. You may do it clicking with the mouse. Or choose one as a default button using Tab and press Enter. Try to press one with the mouse and see what happens. Button body shifts one step to the right and its shadow disappears. The button looks like a "pressed one" on the screen. The action attached to this radio button is carried out as You release the mouse button.

Note that a message on the Calculate button is colored

differently than that on other radio buttons. It means that the Calculate button is a default one inside the dialog box "Choice". Again You may select another button as a default one using Tab and press Enter or Spacebar to choose it.

To the right of every radio button there is a message informing what happens if You choose this button. However if You choose the message, nothing follows.

Choosing the buttons of the dialog box "Choice", You can curry out the following actions:

Cancel - Exit to Main menu (pressing Esc or Close button results in the same action);

Calculate - the display screen is switched to the graphic mode, the Program starts to calculate the given version of the task and simultaneously displays the corresponding picture on the screen. As the calculation is terminated - a menu bar appears at the screen bottom consisting of three items:

P Printer - readout of resulting graphic image to 9-pin printer, W Record_PCX - PCX format filing of graphic information and Enter - Exit to Main menu.

Choosing of other buttons of the dialog box "Choice" results in appearance of dialog boxes closing of which is return to the dialog box "Choice".

A number of control buttons in the dialog box "Choice" depends on history. Always the following buttons are present: Decart, Data, Fon, Cancel, Calculate.

Choice of button Decart results in appearance of dialog box "Decart" allowing to change parameters of Cartesian coordinates connected to the flow. This dialog box has a title, Close box at the far left, two standard buttons: OK, Cancel and two option buttons

noted "choice xs" and "choice ys", offering three versions of choice each, and four input boxes denoted "nxs", "xm" , "nys" and "ym" with history list each.

Choice of button Data results in appearance of dialog box "Data input for spherically symmetrical gas expantion ". This dialog box has a title, Close box at the far left, two standard buttons: OK, Cancel and one option button, offering three versions of choice: "gamma=1.667", "gamma=1.4" and "gamma=1.278". Also there are three input boxes provided with history list each and denoted " a density scale value Nm=", "a spatial scale of the arising GPF b =" and "concentration of ram flow particles NO=" subsequently.

Choice of button Back results in appearance of dialog box "Choice type of GPF". This dialog box has a title, Close box at the far left, two standard buttons: OK, Cancel and one option button, offering three versions of choice: "without background", "background the only", "background added".

Choice of button Input_x results in appearance of dialog box "Input Coordinate x" This dialog box has a title, Close box at the far left, two standard buttons: OK, Cancel and one input box.

Choice of button Level results in appearance of dialog box "Colors and concentration".

Menu Flow

Menu Flow contains commands providing calculation run and resultant data plotting for gas-plasma formations arising due to interaction between released gas jet and space ionizing flux for arbitrary chosen mutual orientation of the latters.

Menu Flow offers five items: Calculate_1, Calculate_2, Calculate_3, Calculate_4 and Calculate_5, each opening submenu of

five commands: FLOW_1, FLOW_2, FLOW_3, FLOW_4 and FLOW_5. Action of these commands depends on the current Program operating mode.

Choice of the commands starts calculation runs of the following task versions:

FLOW_1 - for a gas jet directed upward the ionizing flux;

FLOW_2 - for a gas jet directed along the ionizing flux;

FLOW_3 - for a gas jet directed transversely to the ionizing flux;

FLOW_4 - for a gas jet directed at the angle 0 < beta < 90 to the ionizing flux and

FLOW_5 - for a gas jet directed at the angle 90 < beta < 180 to the ionizing flux.

Choice of any command FLOW_N results in appearance of dialog box "Choice" if the Program operates in the mode "MAIN". Choose the button Data in the dialog box "Choice" and open the adjacent dialog box "Data input for gas jet ... ", if You want to calculate axis-symmetrical task, of the same content as the dialog box "Data input for spherically symmetrical gas expantion " with additional input box denoted "Factor of flow divergency". For non-axis-symmetrical task choose the dialog box with once more additional input box denoted "an angle between ram flow and gas jet beta=".

4. Options.

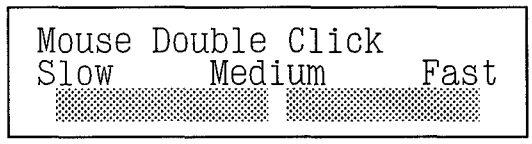
The Options menu contains commands that let you change color and mouse default settings: "Screen sizes", "Mouse", "Colors", "Save Desktop", "Retrieve Desktop" and "Test/Main".

The Mouse command brings up the Mouse Options dialog box, where you can set various options that control how your mouse works,

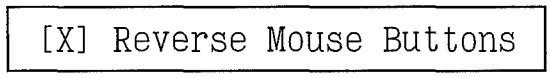
including:

- how fast a double-click is

- which mouse button (right or left) is active This dialog box consists of one check box, one slider bar, and the standard buttons OK and Cancel.

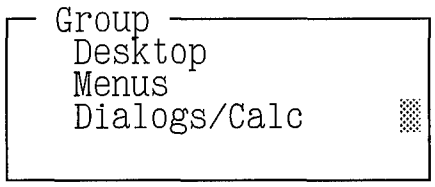


The Mouse Double Click slider bar adjusts the double-click speed of your mouse.

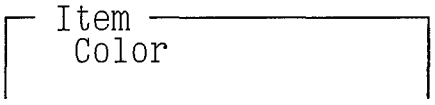


Reverse Mouse Buttons makes the right mouse button take on the normal functions of the left and vice versa.

The Colors item brings up the Colors dialog box, where you can customize the colors of the display. The Colors dialog box consists of two list boxes, a text display area, the standard OK, Cancel, and Help buttons, and on color systems, it also contains two color palettes. This dialog box is where you can change the colors of different parts of this program.

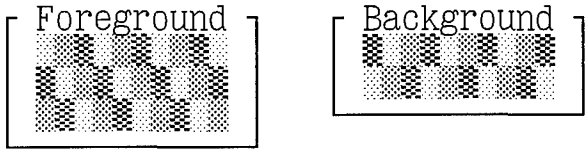


The Group list box contains the names of the different regions of the program that you can customize.

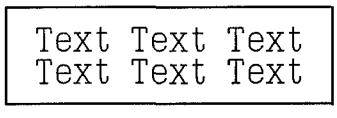


When you select a group from the Group list, the Item list box

displays the names of the different views in that region.



On color system, you use the Foreground and Background palettes to modify colors.



On all systems, the display text (above the Help button) shows the current color or attribute settings. Changes do not take effect on the desktop until you close the Colors dialog box by choosing OK.

Choice of menu name "Screen size" changes numbers of display lines from 25x80 to 43x80 and vice versa.

When you choose the Save Desktop command from the Options menu, you Save the state of all open windows to a file call GPF.DSK. This file can be reloaded by selecting Options|Retrieve Desktop.

Choice of menu name "Test\Main" changes Program mode.

5. Read_PCX.

Choice of menu name Read_PCX. brings up the standard dialog box "Open a File", allowing to choose a file of extension PCX from the file list. An attempt to open a file of another extension brings up a text box with message "File unavailable". Files of extension PCX are files created by the Program to save the resulting graphic information. Choice of any file of extension PCX switches the display screen to the graphic mode and retrieve the image saved. This graphic information also can be red out to a 9-pin printer.